

# 'Bang-Bang' Technique in Supply Modulation for Linear Wideband RF Power Amplifiers

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**Abstract**—This paper deals with the design techniques of power efficient switching regulators intended for linear power amplifiers employing envelope tracking techniques in wideband wireless standards. The bottlenecks involve a tradeoff between ripple voltage, slew rate and bandwidth. The slew rate limitation is identified as the main challenge, then a 'bang-bang' slew-enhancement technique is proposed. This approach enables the use of efficient supply modulators in wideband power amplifiers. The proposed scheme does not significantly degrade PA efficiency and preserves the stability of the switching regulator. The prototype has been implemented using the TSMC 0.18  $\mu\text{m}$  technology; schematic simulation results in Cadence<sup>®</sup> are presented to prove the concept.

**Keywords**—CMOS Technology; Supply Modulator Circuits; RF Power Amplifier Supply; Slew-Enhancement Techniques.

## I. INTRODUCTION

Radio frequency (RF) power amplifiers (PAs) play a key role in transmitting information between places for communication purposes. These forms of communication could be between mobile phone handsets, base stations, computers or Bluetooth devices. The RF PA's main goal is to transmit the information with enough power and spectral purity to drive the antennae. However, the PA is usually responsible for most of the power consumption in the entire transceiver. Additionally, the PA suffers from poor power efficiency, especially when transmitting low power. The stringent linearity requirements in broadband systems makes the linear PAs, particularly class A, the preferred choice in the transceiver. This linearity requirement, coupled with the fact that the PA operates at low transmit power during most of its operation, makes the power efficiency of the entire transceiver poor [1]. The limited power efficiency of the transceiver leads to a reduction in the battery life of portable devices like mobile phones, laptops and MP3 players. This issue of poor power efficiency is also critical in base stations where a high efficiency and low power consumption is important in determining the size of heat sinks for cooling purposes.

In this paper, power management techniques are employed for improving the power efficiency of a class-A PA. An efficient technique to offset the slew limitations of the

switching regulator architecture used in envelope tracking techniques is proposed. This approach alleviates the problem of low slew rate by adding a *bang-bang* controlled current source. The proposed supply modulator promises an average efficiency of 81.6%. A key advantage is that the proposed scheme enables the use of limited clock frequency switching regulators for signal bandwidths up to 20 MHz.

## II. SUPPLY MODULATOR FOR POWER AMPLIFIERS

Wireless transmitters employing envelope tracking techniques are becoming popular nowadays since they provide significant power savings [2]. In envelope tracking techniques, the DSP generates the baseband signal (information to be transmitted) as well as the envelope tracking signal. A supply modulator generates the PA's supply voltage whose output is correlated with the envelope signal. To achieve optimal tracking, the regulator's bandwidth must be higher than the in-band signal bandwidth. The issue is that it is highly desirable to reduce modulator's bandwidth well below the switching frequency to provide enough attenuation to the switching harmonics. Reducing the modulator's bandwidth and clock frequency reduces the switching losses.

The trend of increasing bandwidths and increasing peak to average power ratio of current signal codification schemes such as OFDM makes the design of the supply regulator particularly challenging since it requires wide and fast variations in the supply voltage. The aforementioned conventional switching regulators are very efficient provided that the switching losses and quiescent current consumption are minimized. Thus, clock frequencies cannot be drastically increased. Most existing solutions that deal with these issues combine a linear regulator (or class AB amplifier) in parallel with a switching regulator (architecture referred to as hybrid converters or master-slave modulators) to increase the speed of the supply modulator while maintaining other performances such as small ripple and small switching losses [3]-[6]. However, hybrid converters have the following issues: *a*) relatively high quiescent current consumption; *b*) potential stability issues; and *c*) increased losses due to extra amplifiers.



accommodate envelope variations within this voltage range; and (3) the amplifier must have a high 3 dB corner frequency.

**B. Bang-Bang (BB) Controller**

The bang-bang system is required to provide the slew rate needed by the regulator to follow the envelope signal in the event of fast and large power variations. It consists of a control scheme and a switchable current source which is activated if, and only if, the signal variations exceed the regulator’s slew-rate. The concept is illustrated in Fig. 3. While the input signal speed is within the limits of the regulator’s capability, the BB system is in standby. However, when a fast input signal arrives, the controller, equipped with a digital predictor, enables the BB system increasing drastically system slew-rate thus providing enough current and voltage that maintains the PA operating in linear region.

The bang-bang controller signal  $V_{BB}$  turns on the current source,  $M_{pp}$ , when the output is not able to follow the envelope signal (when the output is slew-limited). The current provided charges up the output node quickly for the output node to follow the envelope signal. The slew rate provided by the BB current-source is given by:

$$I_{BB} > SR_{out} C = V_{max-envelope} \omega_{max-signal} C \quad (3)$$

With  $C=3.6 \text{ nF}$ , signal bandwidth of  $20 \text{ MHz}$  and PA output signal variation of  $1 \text{ V}$ , the current provide by the bang-bang controller must be over  $430 \text{ mA}$ . Larger signal variations may require BB currents above  $1 \text{ A}$ . The bang-bang controller is implemented with a digital predictor and a comparator. In this paper, the predictor is not discussed, only the analog section is addressed.

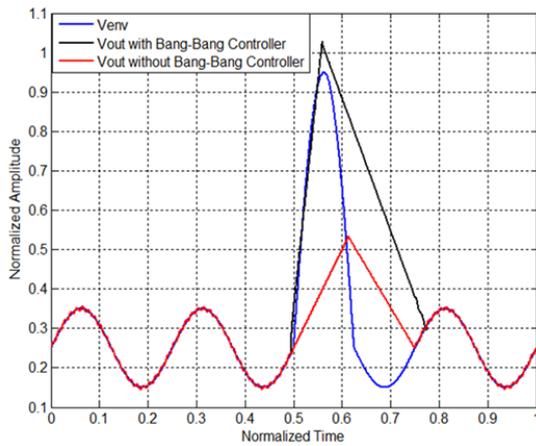


Figure 3. Envelope signal and switching regulator’s output voltage with and without the ideal bang-bang controller.

The critical parameters of the comparator are speed and common mode range. The comparator’s propagation delay is designed to be less than  $2 \text{ ns}$  for a  $100 \text{ mV}$  overdrive. The input common mode range is required to be from  $0.3 \text{ V}$  to  $1.6 \text{ V}$  since the envelope signal varies within this range. Therefore, the comparator is designed to have a rail-rail input stage, as shown in Fig. 4 [7].

**C. Modulator’s envelope control signal  $V_{env-cont}$**

The linear RF-PA is used to test the functionality of the supply modulator. A scaled down version of the envelope signal added to an estimated overhead voltage is used as the reference voltage for the control of the supply modulator according to Fig. 5.

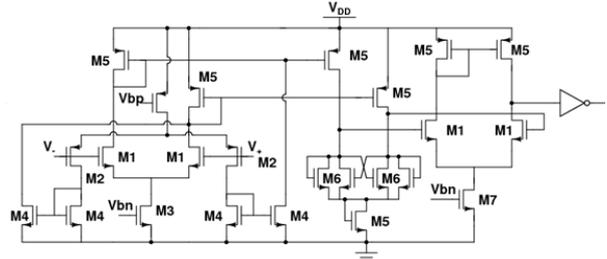


Figure 4. Simplified schematic of the comparator.

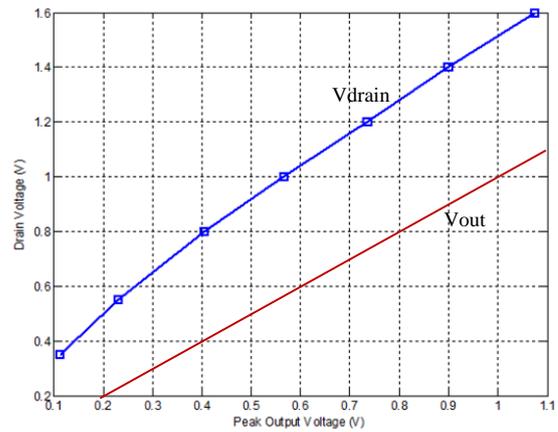


Figure 5. Plot of PA drain voltage against peak output voltage.

**D. Switching Regulator and Selection of L and C**

The power switches  $S_P$  and  $S_N$  are implemented with PMOS and NMOS transistors respectively. The proposed switching regulator is designed for equal switching and conduction losses when the static power consumption is equal to the average power consumption of  $71.5 \text{ mW}$ . The dimensions of the switches are shown in table II.

TABLE II. SWITCH DIMENSIONS AND CRITICAL PARAMETERS

Switch	$W (\mu\text{m})$	$L (\mu\text{m})$	$R_{ON} (m\Omega)$	$C_p (pF)$
$S_P$	3072	0.18	713	8.15
$S_N$	768	0.18	695	2.56

The switching regulator is designed to handle envelope variations with bandwidths up to  $4 \text{ MHz}$  without any help from the bang-bang controller. As a result, the inherent slew rate of the switching regulator should be enough to handle such envelope variations. To achieve this, the slew rate required will be  $16 \text{ mV/ns}$ . Therefore, a relatively large  $L$  and small  $C$  will be the best option because it relaxes the amount of current required by the bang-bang controller to meet the slew requirements. However, for a fixed  $LC$  product, a large  $L$  and small  $C$  cause larger overshoots and undershoot in the presence of load transients; thus, the size of the components have to be carefully evaluated. For this case, with  $L=330 \text{ nH}$ ,

and  $C=3.6\text{ nF}$ , the switching regulator is able to support envelope variations up to  $4\text{ MHz}$  without any help from the bang-bang controller. A switching frequency of  $80\text{ MHz}$  is used for this design.

## V. SIMULATION RESULTS

Fig. 6 shows a plot of the output voltage and the envelope signal for the proposed supply modulator. These plots show that the stand alone switching regulator and the proposed supply modulator have the same performance for envelope signals up to  $4\text{ MHz}$ . Fig. 7 shows that the stand alone switching regulator is not able to handle  $20\text{ MHz}$  variations in the envelope signal (dark dotted line) while the proposed supply modulator is able to closely follow  $20\text{ MHz}$  envelope variations.

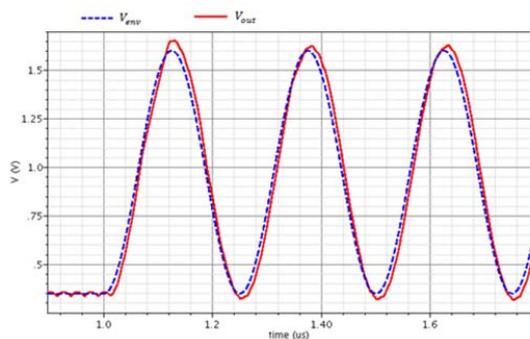


Figure 6. Modulator's output for a  $4\text{ MHz}$  signal.

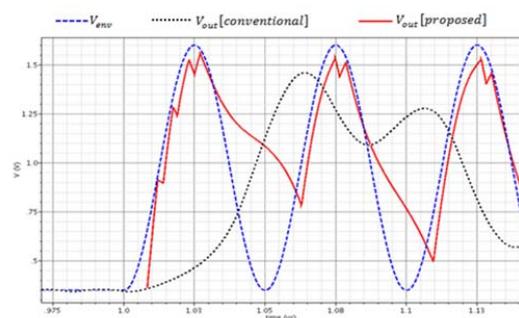


Figure 7. Modulator's output voltage for a  $20\text{ MHz}$  signal.

The efficiency of the supply modulator is obtained from Cadence<sup>®</sup>. This efficiency is obtained for different output power transmitted and plotted in Fig. 8. The average efficiency of the supply modulator is  $81.6\%$ . A summary of performance of the supply modulator with the PA as a load is shown in table III. Table IV shows how the proposed supply modulator compares with state of the art. It is noticed that the proposed supply modulator simultaneously achieves a high bandwidth and high average power efficiency.

## VI. CONCLUSIONS

The design of an efficient supply modulator for linear wideband RF power amplifiers has been presented. The performance of the supply modulator has been shown for bandwidths up to  $20\text{ MHz}$ . The proposed supply modulator has negligible quiescent current consumption, is easy to stabilize, has high efficiency and is simple to design. It

achieves an average efficiency of  $81.6\%$  when used in a CDMA handset.

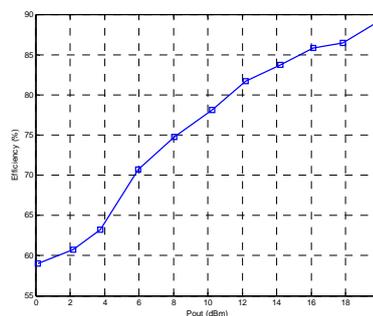


Figure 8. Plot of the efficiency of supply modulator vs. output power.

TABLE III. SUMMARY OF PERFORMANCE OF SUPPLY MODULATOR WITH PA LOAD.

Supply Voltage	2.0 V
Output Voltage Range	0.35 V – 1.6 V
Maximum Output Power (RMS)	19.5 dBm
Quiescent Current ( $I_{bias}$ )	0.92 mA
Maximum Envelope Bandwidth	20 MHz
Switching Frequency	80 MHz
Output Inductance, $L$	330 nH
Load Capacitance, $C$	3.6 nF
Average Efficiency: Supply Modulator	81.6%

TABLE IV. COMPARISON OF RESULTS WITH STATE-OF-THE-ART

	[2]	[5]	[3]	Proposed Architecture
Techn.	180 nm SiGe	65 nm CMOS	350 nm CMOS	180 nm CMOS
Max. BW	20 MHz	20 MHz	2.5 MHz	20 MHz
Average Eff.	65%	*59%	*30%	81.6%

\* Efficiency at 16 dBm.

## ACKNOWLEDGMENT

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