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# CMOS linear high performance push amplifier for WiMAX power amplifier ☆

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ABSTRACT

In this work a novel and efficient approach is proposed to optimize the linearity and efficiency of power amplifiers used in mobile WiMAX applications. A linear and high performance push amplifier is designed and implemented in 0.18 μm CMOS technology to enhance the linearity of a class-E switched-mode power amplifier. The proposed push amplifier consists of two sections; analog and switching sections. The analog section provides required linearity and the switching section guarantees satisfying total efficiency level. Each block is designed and optimized to meet required specifications. The core power amplifier which is a class-E switched-mode power amplifier is also designed to have maximum possible efficiency. The implemented circuit is simulated using HSPICERF and TSMC models for active and passive elements. The proposed power amplifier provides a maximum output power of 25 dBm and a power added efficiency (PAE) as high as 48% at 2.5 GHz operation frequency and supply voltage of 1.8 V. At 1 dB compression point this PA exhibits 23 dBm of output power with 42% PAE and 4.5% EVM which was appropriate for 64QAM OFDM signals.



## 1. Introduction

Recent literatures imply that CMOS PAs can potentially result in major cost reduction in modern wireless products. As a result, there has been a huge interest in developing CMOS PAs [1,2] as an alternative to the prevalent more expensive technologies for PAs such as GaAs HBTs and laterally diffused MOS (LDMOS). Unlike the other technologies, CMOS technology further enables a higher level of integration of digital, analog, and RF components in a single chip, and therefore, can result in much smaller system form factor.

It is important to maximize the power-added efficiency (PAE) for most battery operated radio frequency transmitter systems, especially for handheld mobile wireless applications. Conventional class-AB power amplifiers can offer good PAE at the peak RF output power. However, for non-constant envelope modulation schemes with high peak-to-average ratio (PAPR) such as Wi-Fi and WiMAX, PAs are often forced to operate in the "back-off" region to meet the rigorous linearity specifications, resulting in much lower average efficiency [3,4]. Therefore, nonlinear switch-mode PAs are more efficient than linear PAs. An attractive architecture for enhancing both average and peak PAE utilizes the polar modulation architectures and nonlinear PAs, where the baseband signal is modulated in the amplitude as well as phase. Several researches have demonstrated excellent system efficiency and linearity performances of large-signal polar transmitters implemented by using the envelope-elimination-and-restoration (EER) [5,6] and envelope-tracking (ET) techniques [7–9]. Compared with narrowband applications, WiMAX standard uses OFDMA modulation scheme which presents large PAPR and also need more linearity to meet required specifications. Since a WiMAX signal requires much larger back-off for the PA to be sufficiently linear, it typically results in lower PAE. The emerging WiMAX technology requires PAs to have both features: high saturated output power (+32 dBm) and sufficient linearity. This is mainly due to the high average transmit power ($P_{rms}$~25 dBm at the PA output) and high PAPR resulted from OFDMA modulation (~10 dB) signal required to be transmitted, while still meeting the EVM and mask requirements of 802.16e standard. This strict requirement is further enhanced by the need to keep the PA power efficiency high due to the thermal handling and battery life requirements. In the case of low PAPR signals, the PA works close to its saturated power, and hence achieves higher power-added efficiency (PAE) naturally.

Consequently, there are more challenges on the timing alignment sensitivity, wider bandwidth, and lower distortion requirements for the push amplifier and the PA, while the entire transmitter system still needs to achieve excellent power efficiency. Therefore, in this work, we carefully investigate high efficiency design considerations for a typical ET-based polar transmitter system through experiments and mixed signal (RF/Analog/Digital) total system co-simulations for mobile WiMAX applications.

The rest of this article is organized as follows: in Section 2, envelope tracking power amplifiers is presented. Section 3 proposes a new push amplifier for an envelope tracking power amplifier.

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Section 4 addresses simulation results, and finally the concluding remarks are presented in Section 5.

## 2. Envelope tracking power amplifiers

The block diagram of a typical open-loop envelope tracking polar transmitter system is shown in Fig. 1. In this structure there are two separate paths for amplitude and phase modulated signals. In modern wireless systems push and phase modulated signals can be constructed using $I$ and $Q$ signals which are available in baseband as shown in Eqs. (1)–(3)

$$S(t) = I(t) + jQ(t) = A(t)\varphi(t) \tag{1}$$

$$A(t) = \sqrt{I(t)^2 + Q(t)^2} \tag{2}$$

$$\varphi(t) = \exp\left(arctg\left(\frac{Q}{I}\right)\right) \tag{3}$$

Consequently, in this technique the push and phase signals can be extracted directly from the baseband, and compared to an envelope elimination and restoration transmitter system. An envelope tracking power amplifier can provide the following benefits: (1) no need for push detector and limiter unit; (2) lower bandwidth requirement for the envelope-tracking amplifier, therefore, allowing higher overall system PAE; (3) significantly more tolerance to timing mismatch between the RF and amplitude paths, thus, yielding better linearity performance and (4) reduced RF feedback from the drain of power amplifier's main transistor to the input [10].

In this structure the overall efficiency is dictated by efficiency of push amplifier, because the main power amplifier is usually a class-E switch mode, therefore, its efficiency is high enough to have no effect on the overall efficiency. The phase signal goes through the main power amplifier and the amplitude signal is amplified by the push amplifier. As mentioned in [11] the amplitude of a class-E power amplifier is directly proportional to its supply voltage. The envelope tracking power amplifier uses this phenomenon to modulate the push signal as a voltage supply of the class-E power amplifier. As a result, the push signal is modulated on the output RF signal. In other words, the push amplifier plays the role of dc–dc converter with a variable output voltage, which follows push signal variations and sources the current hungry class-E power amplifier. There are two main challenges in the design of the push amplifier. Based on WiMAX signal specifications, the bandwidth of push signal is reasonably high and reaches up to 10 MHz and it is somehow difficult to implement a dc–dc converter to follow rapid signal variations; on the other hand, the class-E power amplifier needs high current density to deliver a 25 dBm power at the output node, so it makes it hard to achieve a high efficiency dc–dc converter.

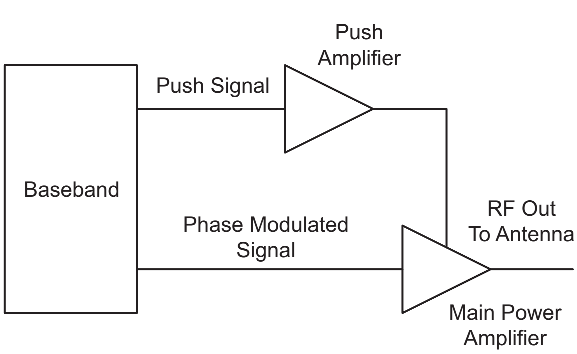


**Fig. 1.** Envelope tracking power amplifier block diagram.

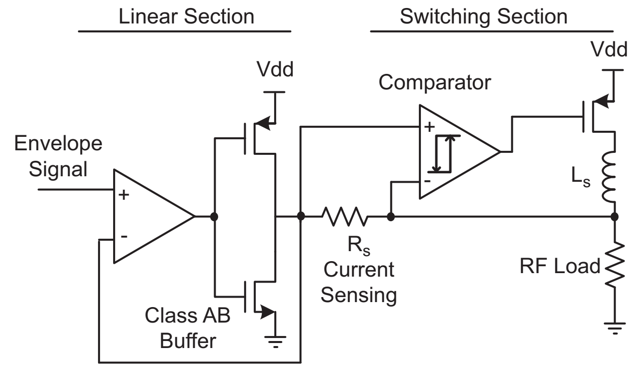


**Fig. 2.** Push amplifier block diagram [12].

The block diagram of the push amplifier is depicted in Fig. 2. There is a principle concept that requires current is supplied from two main sections; the linear section and the switching section. The linear section is consisted of a high speed operational amplifier followed by a class-AB buffer, which provides a linear current for the main power amplifier. It guarantees that the output voltage precisely follows the input variations, but its efficiency is too poor to be acceptable. To compensate the low efficiency of linear section, the switching section is added to source the output node whenever needed. A current sense resistor is used to activate the switch; it means that when a current is sunk from the linear section, the voltage drop on the resistor is sensed by the comparator and toggles the switch on. As a result, the direct current following from the supply makes the output node voltage high enough to inform the comparator to toggle the switch off. Consequently, the contribution of linear section is restricted to high frequency push signals, and remaining parts are provided by the high efficiency switching section.

## 3. Proposed push amplifier for envelope tracking

The block diagram of the proposed push amplifier is shown in Fig. 3. The current sensor resistor (Fig. 2) is replaced by an $I$–$V$ circuit, to prevent from the ohmic loss, because the total linear current flows through $R_{sense}$ and results in the power loss in Fig. 2. In the proposed push amplifier a current mirror ($M_{40}$, $M_{48}$) is used to sample from source and sink current which is flowed through $M_{38}$ and $M_{39}$ (output buffer). A high efficiency $I$–$V$ converter circuit which is followed by output buffer provides a voltage signal proportional to the output buffer current and finally two comparators would control the switches ($M_{70}$, $M_{71}$) to shape up the voltage and current required for the main power amplifier. Using an auxiliary switch which is normally much smaller than the main switch to create a switched discharge path helps to have a smaller linear buffer transistor in the linear discharge path and consequently improves the efficiency as well as the linearity.

The proposed architecture for push amplifier has to meet WiMAX physical layer specifications; the new designed push amplifier must follow input variations up to 10 MHz and also has to source the current hungry main power amplifier up to 250 mA spikes. Each unit of the proposed architecture is to be designed to pass the overall requirements of the push amplifier. As shown in Fig. 3 there is an inductor series with a switching section which constructs a low pass filter together with parallel capacitances of large transistors. The mentioned low pass filter is designed to pass highest frequency elements of the push signal, which the switching section is able to prepare. On the other hand, the switching noise frequency elements are too high to pass through the mentioned filter. Therefore, as it will be shown