Pulse-Width Modulation for Switching Mode Power Amplifiers

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Abstract — **The application of highly efficient switching mode power amplifiers can be significantly broadened to amplify a wider class of time-varying envelope signals provided a suitable pulse train is synthesized for amplification. Pulse-Width Modulation (PWM) is one method for encoding the source signal into a binary level pulse train and can be implemented at baseband or directly at radio frequency (RF) as RFPWM. This paper evaluates the performance of baseband PWM and RFPWM for switching mode power amplifiers. It is shown that baseband PWM has significant advantage in terms of important pulse modulation parameters: coding efficiency, average transition frequency, and pulse width. Thus, switching-mode amplifiers with baseband PWM are expected to achieve relatively better performance. Verified at 800 MHz with a W-CDMA signal and a class-D amplifier constructed using GaN FET devices, 33.1 dBm output power and 59.2% drain efficiency is obtained for baseband PWM, comparing to 31.8 dBm output power and 35.3% drain efficiency obtained with RFPWM. On the other hand, baseband PWM has much higher demands on the bandpass filter (BPF) used at the output of the power amplifier for spur filtering and signal restoring. A class-F parallel amplification topology with three-level interleaving pulse modulation is proposed to suppress the odd-order output spurs and to ease the BPF design.**

Index Terms — **RF power amplifiers, pulse-width modulation, switching mode amplifier, Linearity, Power efficiency**

I. INTRODUCTION

Efficiency of RF power amplifiers (PAs) is of major concern when designing wireless transmitters, and the most efficient RF PAs operate in switching mode. However, when used for modulated signals with a time-varying envelope, switching mode PAs result in excessive spectral growth and loss of modulation accuracy. Thus, the desire to use highly efficient switching mode PAs yet achieving high linearity has been the subject of various research efforts [1-5].

Switching mode PA (SMPA) may be combined with a source encoder to obtain a linear amplifier architecture which can amplify a broad range of communication signals such as QAM and CDMA. The encoder encodes the amplitude varying signals into a binary amplitude pulse train to drive the SMPA in an efficient way. One source encoding method is pulse-width modulation (PWM), which can be implemented at baseband in a pulse modulated polar transmitter or directly at radio frequency as RFPWM. As it was discussed in [4] for ΣΔ modulation, the power efficiency of a Class-D amplifier with source encoder depends largely on how the signal is encoded into a pulse train. While both baseband PWM and RFPWM technique has been employed with SMPAs for efficient power amplification, no work has been done to evaluate and compare their performance. Using a W-CDMA signal, performance of the baseband PWM and RFPWM for SMPA are characterized in this paper by coding efficiency, average transition frequency, and minimum pulse width. The output power, efficiency, and linearity of the overall amplifier are evaluated and analyzed in terms of the performance of the pulse modulators. Further, a class F parallel amplification topology with three-level interleaving PWM is proposed, which eases the high-quality demand on the output BPF used to suppress the out-of-band emissions created by the modulator.

II. SWITCHING MODE AMPLIFIER WITH SOURCE ENCODER

Fig.1 shows a block diagram of the transmitter system employing a pulse source encoder and a SMPA, which as an example is in class-D form composed of two switches. Depending on the state of the driver signal, the switches close alternatively to produce a large amplitude binary level pulse train $p_a(t)$ and from it a load signal is reconstructed by a bandpass filter.

The bandpass reconstruction filter provides nonzero conductance essentially only in the band of interest. It permits the circulation of load current at in-band frequencies and prevents out-of-band current flow. Consequently, there is no power dissipation associated with unwanted spectral components that do not reach the load.

The switching action in the SMPA generates a pulse train, and only zero-crossing of the input signal are preserved after amplification. Since the envelope of the input signal is eliminated by the SMPA, signals with envelope variation cannot be amplified directly and must be encoded in the timing of pulse transitions prior to driving the amplifier.

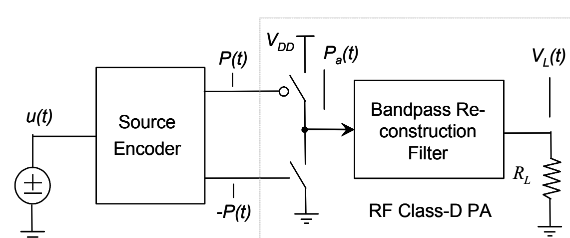

Fig. 1. RF class-D power amplifier with pulse modulator.

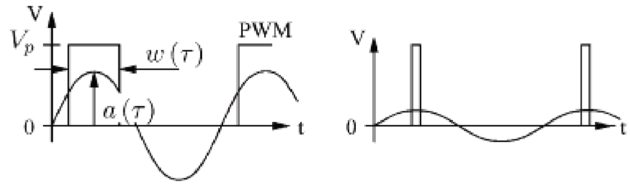

Fig. 2. Principle illustration of RFPWM.

A. RF Pulse Width Modulation

The idea of RFPWM is to produce one pulse in each RF period of a modulated signal:

$$s(t) = a(t) \cdot \cos(\omega_s t + \theta(t)) \quad (1)$$

where $a(t)$ and $\theta(t)$ are the time-varying envelope and phase, respectively, and ω_s is the carrier angular frequency. A RFPWM signal is generated in such a way that the width of the pulse contains the envelope information $a(t)$, and the timing of the pulse contains the phase information $\theta(t)$. This principle is illustrated in Fig. 2. Since the signal information is represented by the width and timing of the pulse, a SMPA can be employed to provide a high power efficiency.

The fundamental-frequency component of a rectangular pulse train is proportional to the sine of the pulse width. Thus, to preserve linear modulation it is necessary to make the pulse width vary as the inverse sine of the modulating signal [1]. The timing of the pulses conveys the phase information. One technique to produce the inverse-sine pulse-width modulation pulse train is to compare the desired envelope $a(t)$ to a full-wave rectified and 90° shifted carrier $|\cos(\omega_s t + \theta(t))|$ [4]. This will produce two pulses with the same polarity per RF cycle. Only one of the pulses per RF cycle is selected to generate a monopolar RFPWM.

B. Baseband Pulse Width Modulation

Baseband PWM is employed in pulse modulated polar transmitters [2]. Fig. 3 shows a block diagram, where the baseband modulation signal is separated into a time varying envelope signal $a(t)$ and a phase signal $\theta(t)$. The envelop signal $a(t)$ is encoded by a PWM modulator to generate a pulse train with different duty cycles that is varied depending on the amplitude information of the baseband signal. The pulse train is then multiplied with a constant-envelope RF carrier containing the phase information $\theta(t)$ to generate a pulsed constant-envelope RF signal. Since the modulated RF signal has only two magnitude levels (1 and 0), it can be amplified by a highly efficient SMPA.

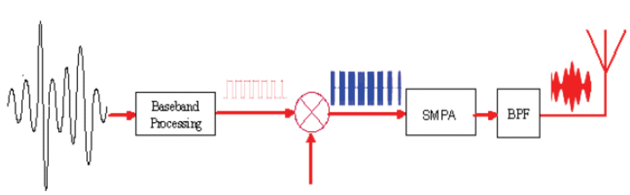

Fig. 3. Baseband PWM for pulse modulated polar transmitter.

III. Performance Evaluation

Performance of RFPWM and baseband PWM pulse modulated driving signals are studied with a class-D SMPA using system-circuit co-simulation in Agilent ADS Ptolemy. Tested with a W-CDMA signal at 800 MHz, a waveform section of the encoded RFPWM pulses and baseband PWM pulse modulated RF signal are shown in Fig. 4. Important modulator parameters: coding efficiency, average transition frequency, and pulse width are evaluated below.

A. Coding Efficiency and Load Power

The source signal cannot be encoded into a binary amplitude pulse train without generating unwanted noise and distortion components. A high level of out-of-band spectral power is wasteful and reduce the utility of the pulse train to generate load power. As a figure of merit to evaluate encoder performance, coding efficiency is introduced and defined as the ratio of the coded signal power relative to the total power in the pulse train [5]. The load power is proportion to the coding efficiency of the modulator. Higher coding efficiency is desired as it increases utilization of the switching devices.

Coding efficiency of a pulse train depends on the signal's peak-to-average power ratio (PAPR) and the modulator design. For the W-CDMA test signal, which has a PAPR of 10.6dB, the calculated coding efficiency of the RFPWM modulated pulse train and the baseband PWM modulated pulsed RF signal is 27.5% and 37.9%, respectively.

B. Average Transition Frequency and Pulse Width

In a class-D amplifier the average power dissipated by capacitive switching losses, which accounts for a significant portion of the total power dissipation, is proportional to the average transitions frequency, f_{av}, of the pulse train. Thus, it is important to have a smaller f_{av}. The monopolar RFPWM pulse has an f_{av} of 2 times the RF frequency. For the pulsed RF signal generated using baseband PWM, the f_{av} is estimated by counting the number of transitions in a sample of the pulse train, divided by its duration. It depends on the PWM frequency and is around 0.62 times the RF frequency for 50 MHz PWM frequency.

Pulse width of a modulated pulse train limits the operation frequency of a class-D amplifier. A pulse width is

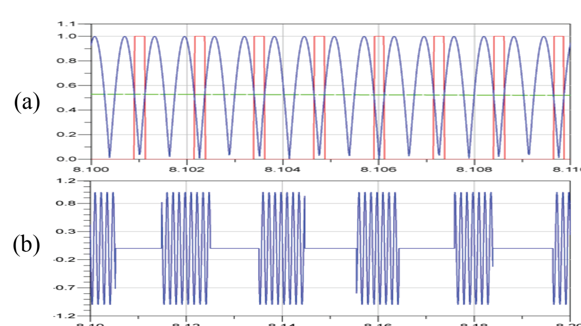

Fig. 4. Waveform section of (a) RFPWM pulses, (b) baseband PWM pulse modulated RF signal.

defined as the time between a succeeding up and down transitions. For the RFPWM over 90% of the pulse width are smaller than 0.25 nS. In contrast, for baseband PWM over 90% of the pulse width has a fixed value of 0.625 nS.

C. Power Efficiency, Linearity, and Operation Frequency

Since baseband PWM has higher coding efficiency and lower average transition frequency, it is expected that the class-D amplifier with baseband PWM performs better in terms of drain efficiency and load power. This is confirmed by the simulation results. For the W-CDMA test signal at 800MHz and a complementary voltage-switching H-bridge class-D amplifier built using a GaN device, an 33.1dBm output power at efficiency of 59.2% is achieved with the baseband PWM, comparing to 31.8 dBm output power and 35.3% drain efficiency for RFPWM. Spectrum of the reconstructed load voltage is plotted in Fig. 5. It shows comparable linearity with spectral growth below -38 dBc.

D. Class-F Parallel Amplifier For Three Level Modulation

The pulse modulated RF signal encoded using baseband PWM contains a wide range of spurious emissions at both sides of the signal band with multiples PWM frequency away, which need to be suppressed by a high-quality BPF. A three-level interleaving pulse modulation can suppress the odd-order output spurs and thus ease the BPF design. The basic method of implementation is to use two PAs in parallel, each controlled by a PWM signal generated using 180^o phase shifted comparison waveforms [5]. However, multi-level pulse modulated signals combined with conventional power combiners can lead to inherent power loss when only partial PAs are turned on.

Class-F parallel amplification as illustrated in Fig. 6 provides a solution [6]. The $\lambda/4$ transmission lines provide class-F harmonic termination as well as a means for power combination. Any of the PAs can be turned off without interfering with the operation of the other branches, achieved by pulling the output of the off PAs to the supply rail to maintain a low output impedance. A 900 MHz 2-branch parallel-amplification class-F PA is designed using a 5W GaN transistor. Fig. 7 shows a prototype photo of the constructed PA. Preliminary test shows that the PA delivers a peak power of 10W with a drain efficiency of 73%. With interleaving pulse modulation of the W-CDMA signal, 34dBm output power and 52% drain efficiency are obtained.

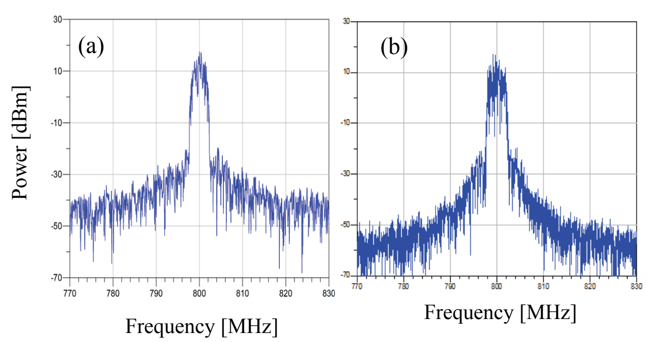

Fig. 5. Output spectrum (a) RFPWM, (b) baseband PWM

IV. Conclusions

The performance of RFPWM and baseband PWM for SMPA have been studied and compared. Baseband PWM has advantage in terms of coding efficiency, average transition frequency, and pulse width. Pulse modulated SMPA using baseband PWM is thus expected to have higher load power and drain efficiency. On the other hand, baseband PWM demands a high quality BPF to suppress spurs. The tight requirement can be relaxed with the proposed three-level class-F parallel amplifier topology.

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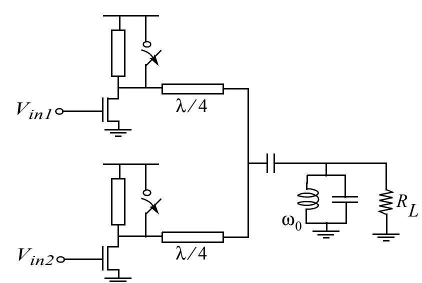

Fig. 6. Class-F parallel-amplification for three level PWM.

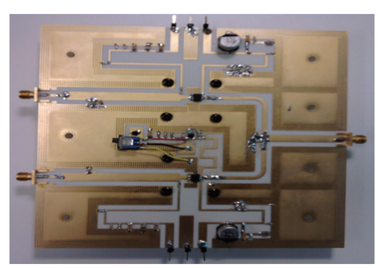

Fig. 7. Prototype of the Class-F parallel-amplification PA.