A High-Efficiency Linear Polar Transmitter for EDGE

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Abstract—This paper discusses a linear polar transmitter for EDGE signals with a total DC-to-RF efficiency of 56%. The transmitter is digitally-controlled, allowing for adjustments of delay, phase and amplitude. The amplifier is a 880-MHz class-E high-efficiency circuit with +20 dBm output power and a PAE of 70%. Two different supply modulators are compared: a 18% efficient linear envelope tracker and a 79% efficient switched-mode envelope tracker. The transmitter meets the EDGE spectral mask for both cases, showing that a high-efficiency amplifier can be linearized with a maintained high overall efficiency.

Index Terms—Polar transmitter, polar modulation, class-E amplifier, envelope tracking.

I. INTRODUCTION

Radio-frequency power amplifiers (RFPAs) dominate the power budget of RF transmitters. Therefore, improving RFP A efficiency by driving the device into saturation can significantly improve the overall transmitter power efficiency. On the other hand, modulated signals for improved spectral efficiency require linear power amplifiers, which are typically operated in backed-off class A or AB mode with efficiencies below 30%.

Supply modulating techniques such as polar modulation [1]-[5] and EER [6]-[8] can linearize non-linear but efficient amplifiers by exploiting the RFP A output power dependence on the supply voltage. Figure 1 shows a diagram of a polar transmitter implemented with an FPGA. The FPGA has three outputs: the amplitude of the complex signal, A and normalized T and Q. Digital-to-analog converters are used at each of the outputs. A is the reference signal to the envelope tracker, while normalized T and Q are the inputs to an IQ modulator. The IQ modulator output is a constant-envelope phase-modulated RF signal. Time synchronization between amplitude and phase modulated paths is crucial since both values determine each symbol.

The envelope tracker supplies power to the RFP A. This means that the overall power efficiency not only depends on the RFP A, but also on the efficiency of the envelope tracker. One way to design ultra high-efficiency envelope trackers is with switch mode power supplies (SMPSs). SMPSs can achieve high efficiencies, are small, light, economic and have the capability to step-up or step-down voltages. However, for these converters losses increase with switching frequency and it is a challenge to design fast high-efficiency SMPSs and the envelope tracker bandwidth needs to be several times larger than the signal bandwidth. In this work, an ultra fast DC-DC buck converter is used as the envelope tracker.

The remainder of the paper presents details of the envelope tracker, the high efficiency power amplifier and the overall polar transmitter performance. This paper builds on earlier results presented in [9], were a Class-E PA with inefficient linear amplifier envelope tracker is described.

II. ENVELOPE TRACKER

In this work, the envelope tracker is implemented with a synchronous buck SMPS and the envelope variations are achieved with pulse width modulation. Deadtime control of the synchronous switches in SMPS is essential to enhance the tracker efficiency and it is implemented with a digital counter-based adaptive scheme. Control is also required to produce a well regulated output voltage in the presence of variations in the input voltage, the load and/or element tolerances. The feedback loop around the power stage also achieves disturbance rejection and sensitivity reduction. The feedback loop also improves the tracking performance when compared to open loop operation. To minimize switching harmonics, the envelope tracker is followed by
a 4th order low pass Bessel filter with cutoff frequency of 1.3 MHz that limits the 2nd switching harmonic below -65 dBc. The filter provides a constant group delay of 259 ns.

Two factors were considered when choosing the switching frequency: signal bandwidth and switcher efficiency. The bandwidth of EDGE signals is 200 kHz. However, for EDGE, the spectral requirements increase when the signal is converted to polar form. The switching frequency was chosen to be 16 times higher than the EDGE standard transmission rate of 270.833 kHz. This corresponds to a switching frequency of 4.33 MHz. The tracker supply voltage is 3.6V, which corresponds to the nominal voltage of a single-cell Li-Ion battery. The maximum output voltage of the tracker is 3.3V. The switcher measured efficiency is 79% [11]. For additional information about the switch-mode envelope tracker, the reader is referred to [12].

The transistor chosen for the PA from Figure 3 is a TriQuint TGF-4240 2.4-mm HFET with an output capacitance of approximately 1 pF. This device is intended for operation up to 12 GHz with a maximal output power of 1 W with 10 dB gain at 8 V drain bias. In the EDGE polar transmitter, the transistor supply is a 3.6-V ion battery with a maximal drain bias of 3.3 V limited by the buck converter.

The PA is implemented as a hybrid circuit that combines transmission lines and lumped elements. Transmission lines are used to present a high impedance to the transistor second harmonic in the form of an open stub. The fundamental frequency input and output matching networks are implemented with lumped inductors and capacitors. The PA output impedance for Class-E operation is \((42 + j48) \Omega\) at 880 MHz. A 10-\(\Omega\) chip resistor is included in the gate input line to eliminate low-frequency instabilities.

Careful attention needs to be given to bias line design to avoid distortion and linear memory effects [18]. The bias line low-pass performance has to be designed to allow for supply modulation at the signal envelope bandwidth. The measured performance of the PA is shown in Figure 4: at 880 MHz, the PA gives +19 dBm output power at 3 V supply voltage with 70% power added efficiency and 11.5 dB gain.

Class E operation is particularly well suited for polar modulation since it can be shown from ideal class-E equations that the output RF voltage across a fixed resistive load \((R_L)\) is linearly proportional to the supply voltage \((V_{SS})\) [16]-[17]:

\[
V_{out} = \pm (26 \cdot f_s \cdot C_{out} \sqrt{R_E \cdot R_L}) \cdot V_{SS}
\]

where \(R_E\) is the real part of the optimal impedance presented to the device for class-E switched mode operation, \(f_s\) is the operating frequency which is also the switching frequency, and \(C_{out}\) is the output capacitance of the active device. From the above equation, the AM-AM characteristic is expected to be perfectly linear. However,
since the device is heavily saturated, the transistor internal capacitances allow feedthrough under low supply voltages as shown in Figure 4c (solid line). The dashed line in the figure shows measured the PA AM-to-PM characteristic and it can be seen that there is significant relative phase difference at low supply voltages. These regions cause distortion. Fortunately, they are avoided in the EDGE modulation scheme since the envelope of the signal is kept above a certain value. For additional information on the Class-E amplifier the reader is refereed to [9].

IV. POLAR TRANSMITTER PERFORMANCE

The diagram shown in Figure 1 is implemented with a Xilinx Virtex II FPGA and commercial oscillator, IQ modulator and DACs. The oscillator is an Analog Devices ADF4360-7 and the IQ modulator is Texas Instruments TRF3701. For testing purposes an EDGE signal segment consisting of 256 pseudo random symbols is stored as a look up table in the FPGA and streamed out repeatedly. Given the standard EDGE transmission rate of 270.833 kHz and an oversample ratio of 8, the signals are streamed out of the FPGA at the rate of 2.17 MHz.

The synchronization of envelope and phase signals is crucial for obtaining linearity, as discussed in [17]. In addition, the DACs introduce a DC offset in the I and Q channels, and compensation is required. Since the envelope tracker is followed by a 4th order Bessel low pass filter it was sufficient to compensate digitally by the filter group delay \( \tau \) in the phase signal path. The implementation from Figure 1 allows all the required adjustments to be performed digitally.

Figure 5 shows the measured output spectrum of the polar transmitter, with the switcher (blue) and the linear amplifier (red) as the envelope tracker. As expected the linear amplifier shows less spectral regrowth (larger bandwidth), but the 79% efficient switcher also meets the EDGE spectral mask.

The RFPA efficiency averaged over varied supply voltage for the EDGE sequence is 71%, while the switch-mode envelope tracker is 79% efficient, resulting in an overall efficiency of 56% with an average RF output power of +20 dBm. The RFPA is able to deliver more than +30 dBm of output power at 8 V drain voltage, however it is desired to use a 3.6 V Li-Ion power battery as the power source. This power source in combination with a buck converter limits the maximum PA supply voltage to 3.3 V thus constraining the output power capabilities of the PA.

V. DISCUSSION OF RESULTS

In conclusion, it is possible to linearize a high-efficiency switched mode RFPA using a polar architecture, while maintaining high overall efficiency. This paper demonstrate a 56% efficient polar transmitter for EDGE. The envelope
A buck-boost topology for the envelope tracker will allow voltage swings above and below the one provided by the 3.6 V Li-Ion battery. Another option is to increase the supply voltage with a slow and extremely efficient boost converter. Amplitude variations can then be accomplished by a fast buck converter similar to the one presented here. In Class-E amplifiers, the voltage across the device can be higher than 3.2 times the supply voltage. Wide-bandgap transistors, such as GaN, can operate at higher voltages and withstand the stress associated with Class-E.

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REFERENCES


